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Functional characterization of L-PBF produced FeSi2.9 Soft Magnetic Material

Michele Quercio, Francesco Galbusera, Emir Pošković, Fausto Franchini, Luca Ferraris, Aldo Canova, Giambattista Gruosso, Ali Gökhan Demir, Barbara Previtali

***Abstract* -- Additive manufacturing (AM) is a production technology attractive for various sectors such as aerospace, biomedical, and automotive. The advantages are various, including being able to create objects with complex geometry and through a careful study of topological optimization, reduce the weight while maintaining mechanical performance. The aim of the present work is to study the feasibility of producing ferromagnetic materials using AM technology for electrical application such as rotor for electrical machine or electromagnetic devices via Laser Powder Bed Fusion (L-PBF). L-PBF is shown to be effective to produce soft magnetic materials (SMMs) such as FeSi2.9. Dedicated test samples with various geometries have been manufactured for evaluating the electrical and magnetic performance under as-built conditions and after annealing.**

***Index Terms*-- Additive manufacturing; Electromagnetic device; FeSi; Laser powder bed fusion; Soft magnetic materials.**

I. Introduction

Additive Manufacturing is a production technology created for rapid prototyping of nonstructural components, mainly for design purposes [1-3]. Around the end of 1990s, it evolved for the manufacture of structural components due to technological evolution [4,5]. The advantage of this technique is to create 3D objects by adding material where needed, following a CAD drawing. This saves material and avoids production waste. A further advantage comes from the fact that it is possible to produce complex or customized parts [6,7]. Through topological optimization, it is possible to reduce the weight of the objects while maintaining their mechanical properties [8-10]. The main technological drawbacks concern the production speed and the elevated costs that can be solved by improving the machine design and productivity [11-13]. Due to the high costs of both material and production (time-consumption), the sectors that first used this technology are aerospace and biomedical.

In the literature, there are numerous example cases of application in these sectors [14-17]. Among the most widely used AM technologies for metallic alloys, Laser Powder Bed Fusion (LPBF) is arguably the most developed one. This technique uses a laser beam to fuse the powder feedstock in a layer by layer fashion. The technique is well established for a limited number of metallic materials such as Ti6Al4V, AISI 316, AlSi10Mg, and CoCr alloys as well as their subsequent heat treatments [18-20]. Recent works showed that L-PBF can be used to produce ferromagnetic material components, while the processability heavily relies on the alloy composition [21-23]. A few examples of the use of AM for the fabrication of ferromagnetic artifacts can be found in the literature where different alloy types such as Fe-Ni, Fe-Co, Fe-Si have been studied [24-26]. In this case, more studies should be conducted to investigate the optimal process parameters, the correct printing direction, and the effects of subsequent heat treatments on electrical, magnetic, and mechanical properties.

Compared to other widely discussed sectors (aerospace, and biomedical), soft magnetic materials produced with AM and their application in the electrical component manufacturing still require further exploration. With an increased demand in electrification especially in the mobility sector, the importance of newly designed components exploiting the geometric freedom of the AM processes with adequate electromagnetic properties become of great interest. Indeed, along with the processability issues the testing procedures of the produced parts and geometries require further attention. Accordingly, this work shows the L-PBF processing and extensive functional characterization of Fe-Si based electromagnetic components in as-built and annealed conditions. Because silicon steels are a very important class of materials for electromagnetic applications as they are widely used in transformers, cores, electric motors, and generators, for this purpose, FeSi2.9 was chosen to be processed by L-PBF. For electrical and magnetic characterization, a rod to evaluate coercivity and a toroid to perform a ring test to evaluate the permeability of the material were produced. After discussing the properties before and after annealing, an example of application is also illustrated in the final paragraphs for completeness of the work.

II. Materials and Methods

A. FeSi Powder

In the present investigation a low – silicon steel powder was processed. The feedstock was produced through powder atomization (m4p material solutions GmbH, Austria). The nominal chemical composition consists of 2.9 wt% Si and Fe bal. The powder had a spherical morphology with a declared granulometry comprised between 20 and 53 µm.

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B. LPBF System

Samples for magnetic characterization were manufactured with an industrial grade LPBF system with open architecture (LLA150R, 3D-NT, Solbiate Olona, Italy). The system is equipped with a fiber laser source (Corona nLIGHT AFX 1000, nLIGHT Inc, Vancouver, Washington, USA), operating with a wavelength of 1070 nm (±10 nm), a maximum power of 1000W and a theoretical waist diameter of 47 µm in the focus position. The laser source can operate either in Pulsed Wave (PW) or Continuous Wave (CW) emission by power modulation. Prior to manufacturing, the building chamber is filled with Ar in overpressure whereas the O_2 content is kept below 3000 ppm. Throughout the experimental activity, ferromagnetic samples were built upon stainless steel substrates.

C. Production of components

The components have been realized starting from a CAD model. The drawing is sliced in several parts and the size of each slice is equal to the height of the layer. Next, the 200W fixed power laser was used continuously to melt the powder in a zig-zag pattern rotating the layers by 67° (Fig. 1). The direction of construction coincides with the axis of the produced part (Fig. 2), except for the toroid that was directed vertically (Fig. 3). The process parameters are listed in Table 1.

TABLE 1 - PROCESS PARAMETERS USED FOR THE FERROMAGNETIC SAMPLES MANUFACTURING.

PARAMETER	LEVEL
POWER, P, (W)	200
SCAN SPEED, V, (MM/S)	800
HATCH DISTANCE, H_D, (µM)	70
LAYER THICKNESS, Z, (µM)	30

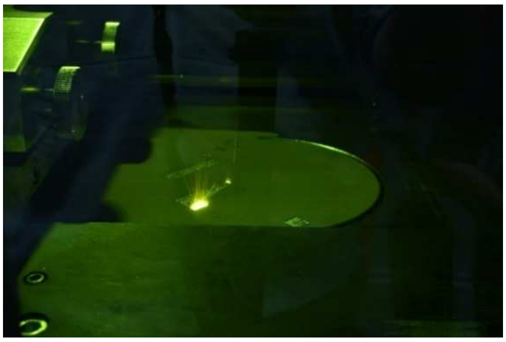


Fig. 1 - LPBF System

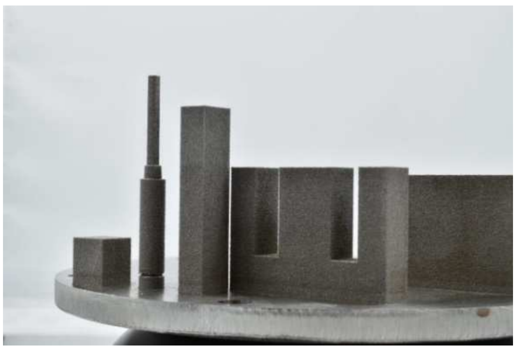


Fig. 2 - Components made of FeSi2.9 material

Fig. 3 - FeSi2.9 Toroidal Sample: outer dimeter 13.35 mm, inner dimeter 9.58 mm and thickness 2.25 mm

III. MAGNETIC CHARACTERIZATION

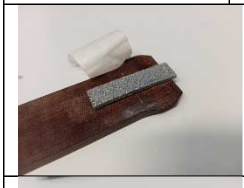
The magnetic properties of produced components are detected to understand the possible relevant applications. The technique used to identify magnetic and energetic behavior are coercivity measurement and toroidal magnetic test. Also, the Single Sheet Tester (SST) can be applied, but the specimens require very high planarity. The used procedure is more similar to bulk or Soft Magnetic Composite (SMC) materials characterization instead of laminated steel [27]. Furthermore, the analysis has been conducted considering the measurement before and after heat treatment at 1200°C, 1h, in vacuum as suggested in [28].

A. Coercivity Measurement

A very quick and reliable measurement could make evident the effects of the heat treatment on the magnetic hysteresis. The coercivity value (Hc) measured in a very slow transient is highly related to the area of the hysteresis cycle. A controlled power supply, an excitation coil and two sensing coils are the main parts of the adopted coercimeter (Fig. 4). The maximum magnetic field value reached in the saturation phase is 100 kA/m, while the Hc point is reached in 10 seconds, limiting most of the eddy current contribution. In Table 2 the results confirmed the expected material behavior: an important reduction is evident of the residual stresses due to the fast cooling cycles induced in LPBF process, as can be seen by the strongly reduced values of the thin and thick bars. The cylindrical rod showed a low coercivity value even before the treatment: this behavior should be better investigated in the future, as it can be related to the specimen shape or to the printing conditions of such a small diameter.

Fig. 4 - Specimen insertion in the coercimeter coil

TABLE 2 - COERCIVITY VALUES BEFORE AND AFTER THERMAL TREATMENT

Specimen Shape	No treatment (A/m)	Treatment at 1200°C in vacuum (A/m)
	212	85.6
	151.6	94.6
	87.7	69.1

B. Toroidal Magnetic Test

The tests involved the use of a soft material hysteresis graph operated at different frequencies between 10 Hz and 1 kHz. The measurements were limited to an excitation field peak of 6500 A/m or to a secondary voltage peak of 10 V.

The toroidal sample was equipped with two windings: the secondary one, thinner, directly on the sample surface and the primary one on top of the former, as shown in Fig. 5.

The toroid dimensions were somewhat too small if compared with the requirements of the IEC 60404 series standards, leading to a slight underestimation in the dynamic iron losses at the mid-low frequencies. The hysteresis contribution was always correct instead.

The comparison between the measurements conducted before and after the heat treatment shows different properties of the material, and helps to tune the next steps of the research activities. The main differences involve the maximum magnetic permeability and the total iron losses.

The magnetic permeability before the heat treatment is rather lower than expected for the adopted powder composition (Fig. 6), mainly showing a poorly relaxed state of the crystal lattices. Consequently, the magnetization curves are too narrow and smooth (Fig. 8). The maximum magnetic permeability value is 748 and magnetic induction does not exceed 1.1 T without the heat treatment.

The iron losses measured before the heat treatment show a rather low electrical resistivity, with the full cycles at 1 T losing their tips, but only at 500 Hz and 1 kHz. The hysteresis contribution is anyway rather high at all frequencies, as shown in Fig. 10 and Fig. 11.

Fig. 5 - FeSi2.9 Toroid: size and shape not fully compliant with the IEC 60404 series standards

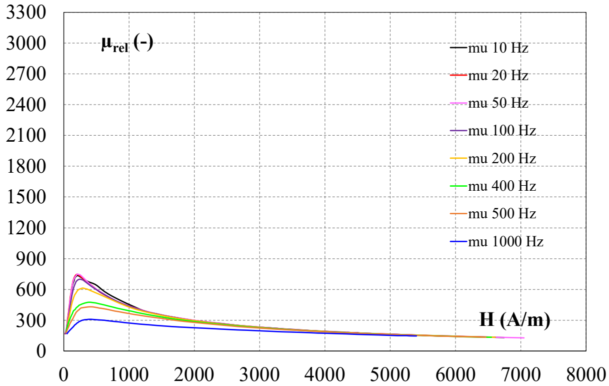


Fig. 6 - Magnetic permeability as a function of magnetic field H at different frequencies for FeSi2.9 toroid without treatment

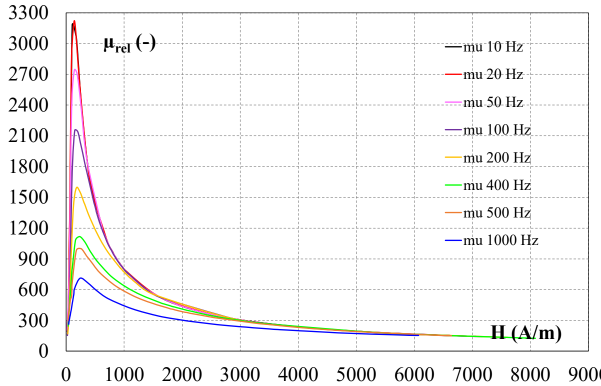


Fig. 7 - Magnetic permeability as a function of magnetic field H at different frequencies for FeSi2.9 toroid with the treatment at 1200°C

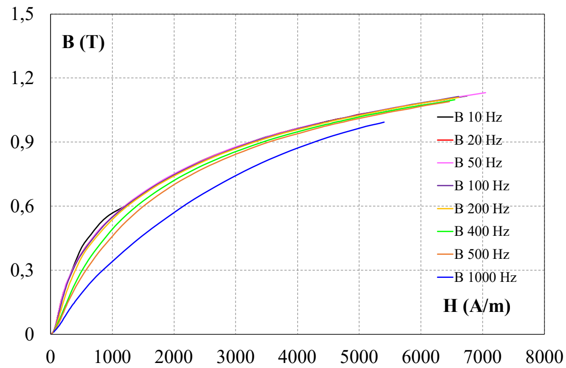


Fig. 8 - Magnetization curves at different frequencies for FeSi2.9 toroid without treatment

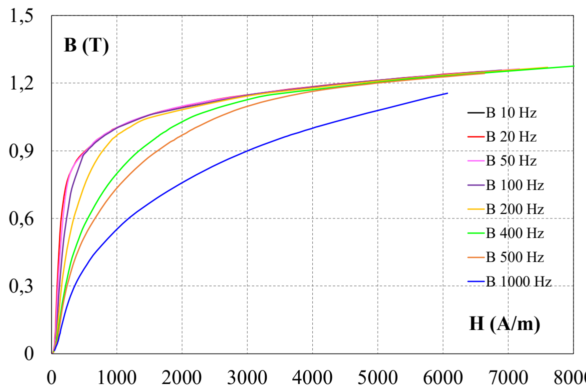


Fig. 9 - Magnetization curves at different frequencies for FeSi2.9 toroid with the treatment at 1200°C

The magnetic permeability raises consistently after the heat treatment (Fig. 7), bringing the hysteresis contribution to the iron losses at very low levels. The maximum magnetic permeability after the treatment corresponding to 3224 and magnetic induction show values greater than 1.2 T (Fig. 9).

The total iron losses after the heat treatment surprisingly decreased at all frequencies and for any peak induction value as reported in Fig. 12 and Fig. 13, showing that the heat treatment benefits fully compensate for the reduction in global electrical resistivity.

The hysteresis cycles before the treatment are reported in Fig. 14; it is possible to note the high presence of hysteresis losses together with the contribution of eddy currents. The full cycles at 1 T show a strongly reduced electrical resistivity, typical of a fully sintered internal structure (Fig. 15), in which the main part of the iron losses is dynamic and originates from the eddy currents.

The additional particular investigation concerns the maximum magnetic permeability as the function of the frequency, as shown in Fig. 16. The reduction is more pronounced after the heat treatment, and at 100 Hz the reached value is 50% compared to the maximum one. A similar percentage decrease is obtained at 400 Hz for no heat treatment. The iron losses @1T for various frequencies are shown in Fig. 17. The values for with and without heat treatment are very close to each other, where the values corresponding to heat treatment are slightly minor.

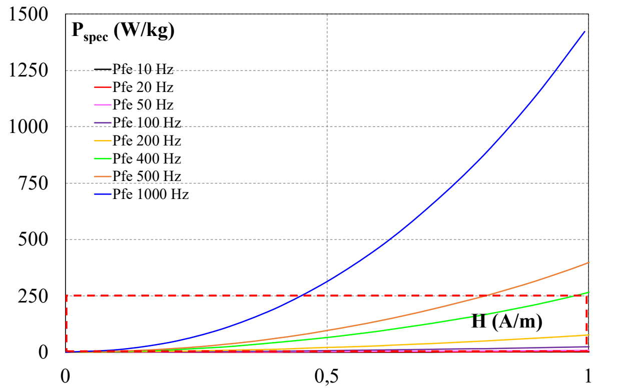


Fig. 10 - Specific iron losses as a function of magnetic induction at different frequencies for FeSi2.9 toroid without treatment

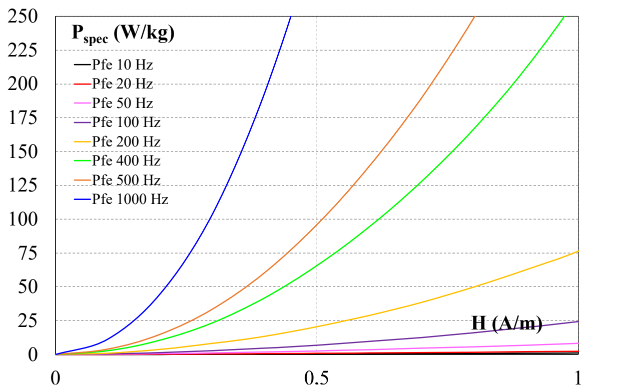


Fig. 11 - Specific iron losses as a function of magnetic induction at different frequencies for FeSi2.9 toroid without treatment: restricted to 250 W/kg

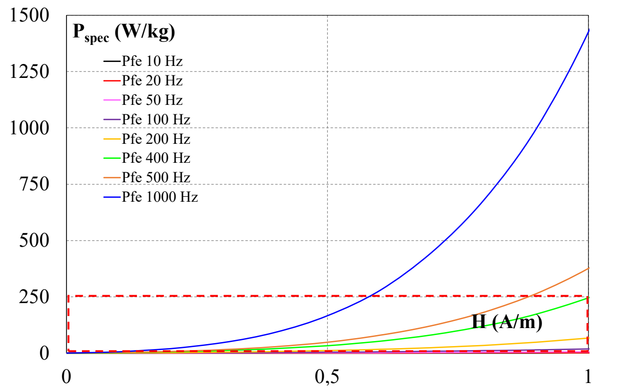


Fig. 12 - Specific iron losses as a function of magnetic induction at different frequencies for FeSi2.9 toroid with the treatment at 1200°C

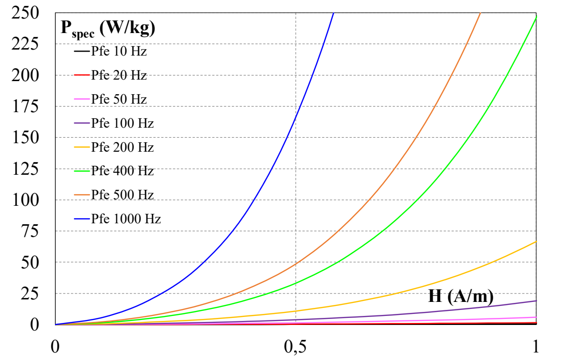


Fig. 13 - Specific iron losses as a function of magnetic induction at different frequencies for FeSi2.9 toroid with the treatment at 1200°C: restricted to 250 W/kg

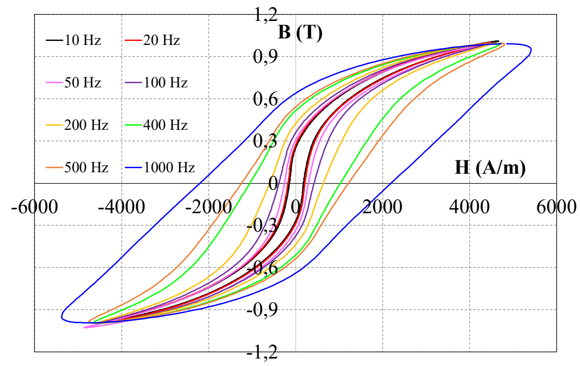


Fig. 14 - Hysteresis cycles at different frequencies for FeSi2.9 toroid without treatment

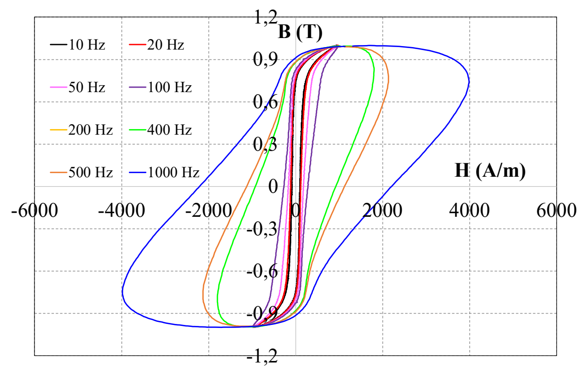


Fig. 15 - Hysteresis cycles at different frequencies for FeSi2.9 toroid with the treatment at 1200°C

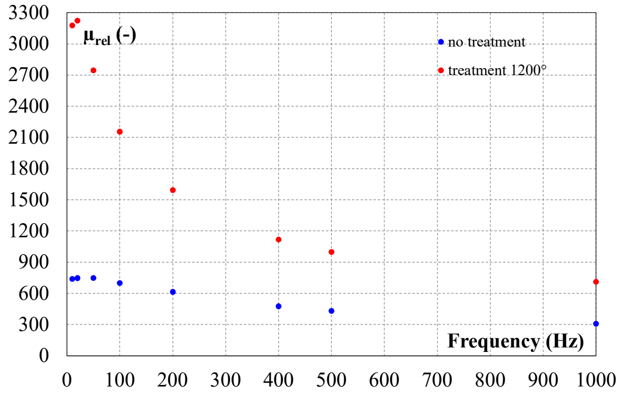


Fig. 16 - Comparison between magnetic permeability before and after thermal treatment as a function of frequency

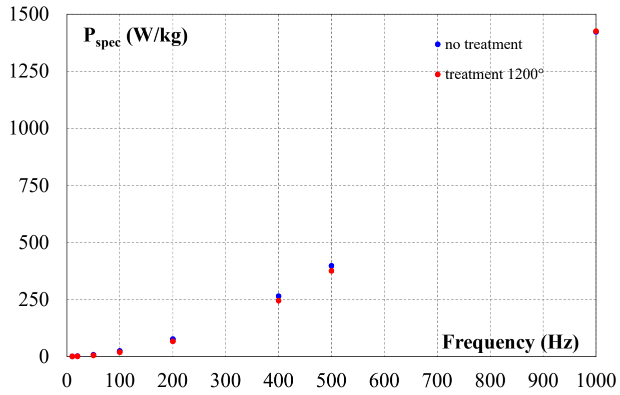


Fig. 17 - Comparison between specific iron losses before and after thermal treatment as a function of frequency

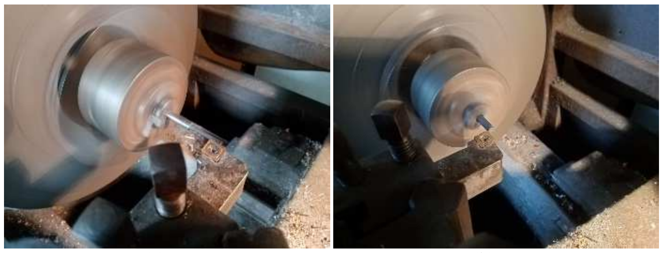
IV. APPLICATION

One of the produced FeSi samples fits as the cursor in a small magnetic piston. This device bases on a coil, magnetically pulling an inner solid cursor. The used model is of the single effect type, thus including a counteracting spring. The nominal voltage of the device is 12 Vdc.

After the LPBF process, the sample needed to be machined to obtain smooth surfaces and the thread for the end damper and nut (Fig. 18).

The tests on the device with the original and the newly produced rods, shown in Fig. 19, leaded to a direct electrical and mechanical comparison between the materials.

During the tests, a voltage step at the nominal level (12Vcd) caused the cursor movement until the natural stop position (Fig. 20). The recorded voltage and current waveforms are shown in the figures (Fig. 21,Fig. 22, and Fig. 23). Due to the reduced force on the FeSi cursor, the spring was not included in the setup and the initial cursor position was moved from the completely open one, to an intermediate one, so that the total stroke was in any case 10 mm.

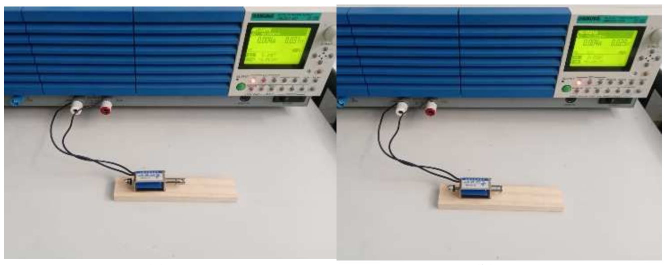


(a) (b)

Fig. 18 - Removal of front (a) and side (b) roughness

(a) (b)

Fig. 19 - The original and FeSi2.9 plunger (a) and solenoid closing system (b)N



(a) (b)

Fig. 20 - Plunger closing measurements: original (a) and FeSi2.9 (b)

In the first transient test, the coil had no cursor inside, so that only the electrical contribution to the current transient is visible (Fig. 21).

The presence of the cursor in the second and third tests changed the current waveform, clearly showing the cursor travel phase and the time at which, the movement completed. The latter can be easily detected as the last current slope inversion, after which the current completes the exponential transient following the higher final inductance value.

The main result is to show that the lower force acting on the FeSi rod causes a reduced acceleration (Fig. 23), with a longer travel time, with respect to the original rod (Fig. 22).

Future improvements to the test bench could lead to the measurement of the transient speed trend or of the force acting on the cursor at different positions.

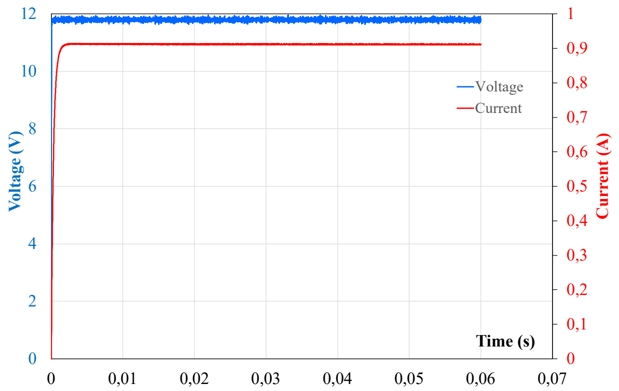


Fig. 21 - Initial current transient: Solenoid only

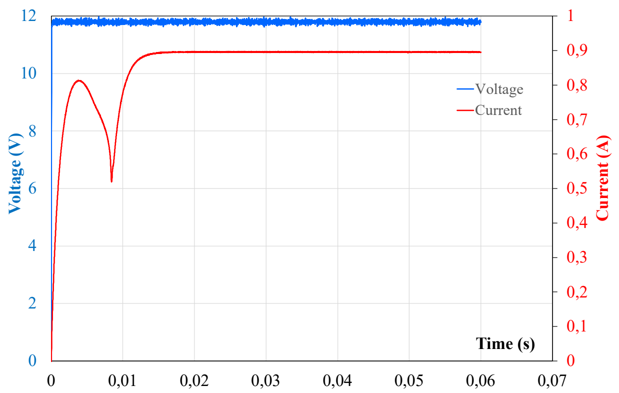


Fig. 22 - Initial current transient: Original small plunger

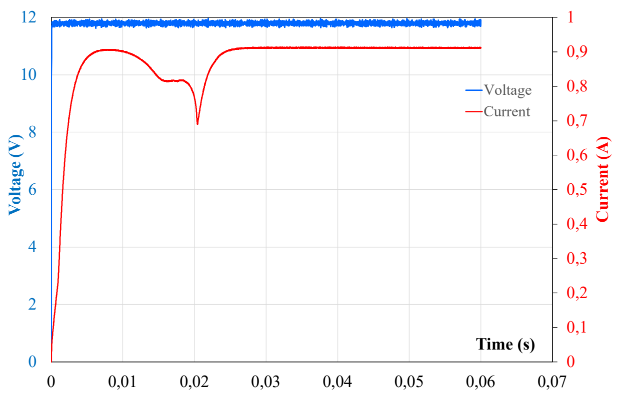


Fig. 23 - Initial current transient: FeSi2.9 small plunger

V. CONCLUSION

The above results are a beginning of investigation of the application of additive manufacturing to produce ferromagnetic components. As can be seen from the analyzes shown, the printing parameters and the type of heat treatment greatly affect the electrical and magnetic characteristics of the pieces produced. The electrical conductivity after heat treatment increases considerably, getting very close to the theoretical values for the alloy. For this reason, the lower losses due to hysteresis (narrower and longer cycle in B) are unfortunately compensated by greater losses due to eddy currents (mentioned in the text), which notoriously increase with the frequency, overall, hysteresis losses have been reduced. Future work will focus on the use of new ferromagnetic alloys and on the possibility of making components with geometries that reduce the effects of eddy currents.

VI. ACKNOWLEDGMENT

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VIII. Biographies

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